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An Experiment to Transfer Angular Momentum from a Helical Low Energy Proton Beam to a Trapped Electron Plasma

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Abstract. As part of a continuing program of beam-plasma interaction studies, a low energy (2 -10 keV) proton beam will be injected on a helical trajectory into a trapped electron plasma in a 1.6 T cryogenic solenoid. The proton source is a conventional duoplasmatron, but operated well below its design extraction energy. Beam tests over the desired energy range have established a mode with submillimeter beam focus and currents of a few μA. The beam will be transported into the high field, displaced, and then inflected by a sudden impulse onto an offset helical trajectory of low pitch. The electron plasma trapping potential will provide a fine pitch control and will serve as an analyzer of the residual longitudinal momentum (helix pitch). Previous experiments in this laboratory employing proton beams of high energy (50-300 MeV) in a storage ring have shown that an electron plasma absorbs angular momentum and energy from the proton beam - for example exhibiting expansion through beam misalignment which breaks the trap azimuthal symmetry. The expectation is that a lower energy beam, traversing the plasma at velocity well below that of a typical wave mode, may be more effective in torque transfer. A possibility may exist for significant plasma compression with judiciously chosen settings of the helix position offset relative to the plasma surface. Progress in design and implementation of the low energy injection scheme will be presented.

INTRODUCTION

In the past few years, a proton beam in the Cooler storage ring at the Indiana University Cyclotron Facility (IUCF) has been used for first tests of the response of an electron plasma to a passing fast beam. Initial experiments indicated an energy transfer from beam to plasma which was substantially larger than predicted from single particle collision rates, and which exhibited variation from one beam exposure to the next — indicative of some significant uncontrolled parameter. A non-destructive monitor of plasma radius was then developed [1] so that transfer of energy and angular momentum could both be observed. With this new capability it was found that the beam torque on the plasma was unexpectedly sensitive to beam translations and rotations with respect to the trap symmetry axis. In particular, the beam angle was identified as the uncontrolled parameter in the early studies. A description of this work is being prepared for publication elsewhere.

The beam in the storage ring is fast and rigid, so that particle velocity (v/c > 50%) is much larger than plasma wave or thermal velocities (v/c < 2%). The beam is thus unlikely to participate in the dynamics through two-stream instabilities. We suspect that

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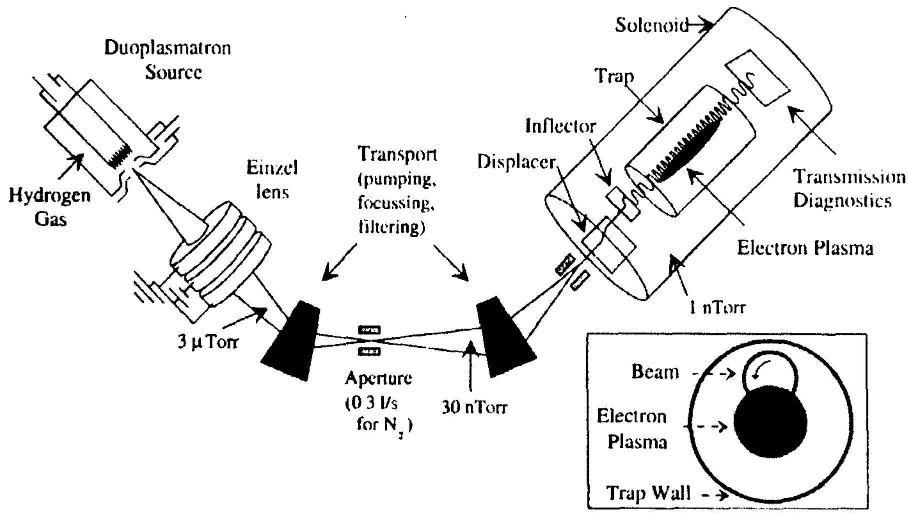

FIGURE 1. Beam-plasma layout in the laboratory. Inset gives an end view of the "corkscrew" beam interacting with the electron plasma.

the plasma density perturbation (the plasma attempting to screen out the beam collective field) is being dragged through the rotating plasma by the immovable beam and the resulting viscous drag is responsible for the observed torque.

The experiment whose preparation is described in the present report is an attempt to probe the beam-plasma interaction in the opposite beam velocity limit. Using ion source technology we can prepare a beam of protons in a much lower velocity range ($0.2\% < v/c < 0.5\%$). We have designed transport elements to carry this beam into the high field trap solenoid, to produce controlled displacements, and to convert longitudinal into transverse momentum so the beam path is a helix of variable pitch. By analogy to electron cooling, the angular momentum of the beam helical motion may be transferrable to the plasma. The proton helix rotates at the cyclotron frequency while the electron plasma counterrotates at the rotation frequency of drift motion in its self electric field(see inset Figure 1).

SOURCE AND TRANSPORT

A hydrogen-fed duoplasmatron ion source will produce a beam whose principle charged components are protons, H_2^+, and H_3^+ [2]. By operating the source far below its intended extraction voltage, we have produced beams with kinetic energies as low as 1keV. Downstream sector magnets allow for the isolation of any of the three ion species, and by employing an einzel lens, proton beams have been focused to sub-millimeter diameter.

The duoplasmatron source has a turbine pumping the chamber adjacent to the extraction aperture. This region maintains a pressure of about 3 μTorr, with the source H_2 gas flow somewhat below the value giving maximum ion current. As the electron plasma

tolerates a background pressure of about 3 nTorr, a drop in pressure along the transfer beam line of order 10^3 is needed.

We take advantage of the small beam waist after the first bend to insert a conductance-limiting aperture of 8 mm diameter and 100 mm length where the transition from elastomer seals to bakeable all-metal construction is taking place. The 75 l/s ion pump at the second bend is expected to bring the pressure in this region to the 10^{-8} Torr range.

The final beam waist is located within the displacer in the trap chamber so the last conductance limiter must have a bigger aperture and will reduce the pressure by only about one order of magnitude. If necessary, a second turbopump, normally used for roughing, can be attached to the first magnet chamber after the lens aperture to obtain a further reduction. A schematic layout is given in Figure 1.

DISPLACER AND INFLECTOR

When the beam enters the solenoid it is converging and traveling along the axis of trap. An electrostatic mirror placed on the axis of the trap would convert some of the beam's momentum from parallel to perpendicular to the trap axis, but the range of possible helix radii and guiding center locations would be severely limited, therefore inducing helical motion will be done in two steps. First, an electrostatic displacer radially shifts the beam off-axis, then an electrostatic inflector gives the offset beam a transverse kick to induce cyclotron motion about a magnetic field line.

For displacement, employment of drift motion within the high B field adjacent to the trap is ruled out by space constraints. Because a low-energy beam of finite diameter is spread by the momentum-position correlation (dispersion) imposed as the beam enters the E field element, an E field magnitude $E_0 < 0.1$ MV/m must be used giving a device length >0.2 m.

The displacer is instead located in the throat of the solenoid. The first bend pair occurs in a weak B field and the second bend pair in a moderate B field so the beam exits along a field line (Figure 2). By employing (x, y) pairs, the cyclotron motion can be compensated over a range of beam energies and trap B field strengths. Compensation fails if bends in either plane are separated by an integer multiple of half-gyrowavelengths. In practice this means that the last deflector element lies at $B/B_o < 10\%$. The steel jacket of the solenoid produces a rapid falloff of B (half-length about 0.05 m) in the displacer region which is essential to the selected design.

The four E field values of the displacer plates are to be adjusted so coherent cyclotron motion is minimized. In this way the tuning of the displacer and of the following inflector is largely decoupled.

The inflector is designed to accept a beam of charged particles moving along a B field line in a strong uniform field and to convert most of the momentum from parallel to perpendicular to the trap axis. Note that the adiabatic invariant responsible for mirroring must be broken to do so. A localized electric field impulse will serve provided the time duration is short compared to the cyclotron angular period ($\frac{qB}{m} * dt < 1$).

A planar electrostatic mirror with small gap, tilted at 45°, will give a 90° deflection in the low B limit. The mirror potential qV must exceed half the beam ki-

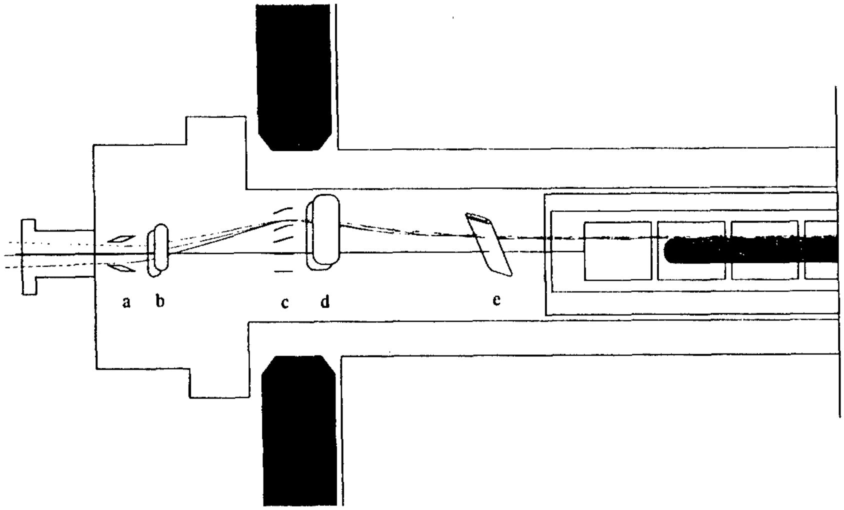

FIGURE 2. Side view of a numerical simulation of the beam being displaced by the four electrostatic elements (a-d) that make up the displacer. The inflector's position is shown (e) for reference.

netic energy T, which limits the concept to beam energies of a few keV. The uniform longitudinal deceleration $a_z = \frac{qE_z}{m}$ reduces the incident speed $v_{z_0} \simeq v = (\frac{2T}{m})^{\frac{1}{2}}$ to zero in time $dt = v/a_z < \frac{m}{qB}$ or rearranging $a_z * \frac{m}{q} = E_z > v * B$ so the force inside the gap is mainly electric. For protons with $\frac{v}{c} = 0.5\%$ (T = 11.7 keV) and B = 1.6 T, this means $E = \sqrt{2}E_z > 2.4$ MV/m. Note the resulting constraint on gap g since $V = g * E > \frac{T}{2q}$, with $E_z = \sqrt{2}E > (\frac{1}{8})^{\frac{1}{2}}(\frac{T}{gq})$. If we choose the minimum E_z then $g > (\frac{1}{8})^{\frac{1}{2}}(\frac{T}{qvB}) = (\frac{1}{8})^{\frac{1}{2}}(\frac{mv}{2qB}) = (\frac{1}{32})^{\frac{1}{2}}R$ where $R = \frac{mv}{qB}$ is the radius of the cyclotron orbit after inflection (R = 9.8 mm, g > 1.75 mm for the speed chosen above). Tracking simulations show that $dt < (\frac{\pi}{2}) * (\frac{m}{qB})$ is tolerable so that we choose g = 2.5 mm and E < 2 MV/m for the inflector mirror.

After leaving the mirror, the cyclotron motion about a fixed guiding center would lead to a second mirror encounter and to the beam returning along the incident direction. The mirror angle must therefore be reduced, and the mirror must have an edge so the helical path wraps around the edge with sufficient pitch to clear the backside. By tilting the mirror about a second axis normal to the field and to the first axis, the encounter may be delayed until a full cyclotron period giving a minimum pitch = 2g. The proper choice of the two direction cosines which specify the double tilt gives a similar minimum pitch over the design range 5 < R < 10 mm. Figure 3 shows tracking through a planar mirror with semicircular ends to illustrate this point. The view is down the gap. The E field is generated from a 2D relaxation. Note the spread in pitch caused by field non-uniformity in the end region at the lower rigidity. Periodic focussing by the regularly spaced grid wires contributes to the spread in helix pitch, but is omitted here for clarity.

The longitudinal velocity at 1.6 T and 5 mm pitch is v/c = 0.04% with a stopping potential of 75 eV. This potential is in the range of the electron trap end potential so it

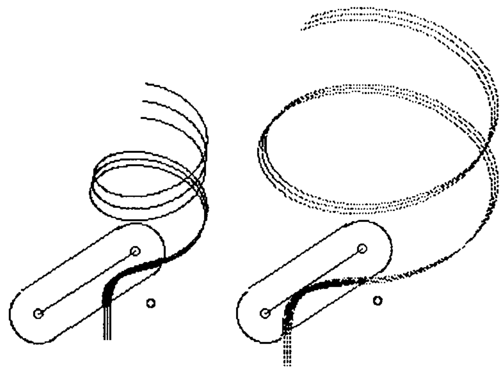

FIGURE 3. Doubly-tilted inflector imparts helical motion to beam entering from below along B=1.3T field. Proton beams of 2keV with E=0.6kV/mm (left), and 8keV with E=1.6kV/mm (right), give helix radii of 5 and 10 mm respectively. Note that entering the non-uniform field of the semi-cylindrical end (in order to obtain clearance at the lower energy) results in an increased spread in helix pitch. The starting rays are separated in x by ±0.3mm. The auxiliary steering wire on the lower right is unbiassed in these examples.

is possible to further reduce the longitudinal velocity as the proton helix enters the trap. This reduction is discussed in the following section.

BEAM-PLASMA INTERACTION

The electron plasma is confined axially by an inverted potential well which is formed by keeping the end rings of the trap at ground potential and floating the center of the trap near 200 V. A positive charge entering the trap will be slowed parallel to the axis by the plasma trapping well. For a beam on a helical trajectory this slowing occurs and causes a decrease in pitch or complete reflection of the beam. The decreased pitch is advantageous since the beam rotates more and interacts longer with the plasma before leaving the trap. The fact that the plasma potential reduces the well potential near the axis means that beam particles nearer the axis of the trap will not be slowed as much as ones near the wall of the trap as is seen in the numerical simulations of Figure 4. In the figure, the beam can be seen to rotate about the trap axis as it travels the length of the plasma. The presence of the plasma's radial electric field introduces an $\mathbf{E} \times \mathbf{B}$ drift about the trap center that would not be present were the plasma not there. Note that, though the electric field is weaker for the beam outside the plasma than for a beam on the edge of the plasma, the reduction of the former's helix pitch gives it more interaction time for the drift to take place and gives both beams a similar precession angle while passing the plasma. Though the precession of the beam helix will complicate post-interaction beam diagnostics, it will have little effect on the torquing mechanism.

Adjusting the beam helix position and radius will allow for the application of different torques. A compressional torque is expected when the helix straddles the plasma surface, whereas an expansion torque should be seen when the beam and plasma are coaxial.

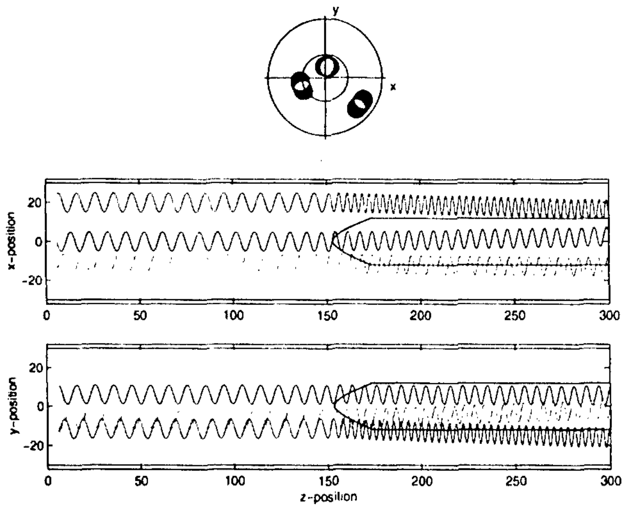

FIGURE 4. Numerical simulation of protons on helical trajectories fired at an electron plasma trapped in a negative potential energy well. The well is created by a cylinder of radius 30 being grounded except for $z \geq 150$ where the cylinder potential is positive.

STATUS

The electron plasma portion of the setup was placed in service last year. The proton source was commissioned at the start of 2001, and designs of transport, displacer and inflector elements have been developed based on measured beam properties. We are presently waiting for UHV welded vacuum components to emerge from our shop. The tests of proton beam properties in the empty solenoid should then be followed by the first slow beam-plasma studies later this year.

ACKNOWLEDGMENTS

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